# Dissertation Title

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## Declaration

I hereby certify that this material, which I now submit for assessment on the program of study as part of Master of Science in Dependable Software Systems qualification, is *entirely* my own work and has not been taken from the work of others - save and to the extent that such work has been cited and acknowledged within the text of my work.

Signed: Date:

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## Abstract

Formal specification and software verification of software have become increasingly pertinent in the past decade, as a way of supplementing the already popular software testing techniques, to both improve software quality and provide a more concrete proof of reliability. However, the use of these proof techniques has not been wholly adopted by industry due to business factors such as the time required for specifying the source code and costs related to such a process, to the more technical factors such as the difficulty in specifying and verifying code with the current tools and languages available, with an expert in the domain often required to get valid implementations.

In this project we will be focusing on a verification tool called OpenJML, developed by David R. Cok with Java as its target language, that set out to simplify the development of specifications using the JML language and simplify the verification process using SMT provers, with the overall goal of wide adoption by industry professionals. This project sets out to examine, the updated version of this tool, to see if a novice user can adopt the techniques required to specify and verify pieces of software. We plan to determine OpenJML’s validity as an industry alternative in comparison to similar existing verification tools, and to examine its performance as a standalone specification and verification tool.

**Category, Terms, Keywords: OpenJML, Formal Specification, JML, KeY, Why3, Deductive Verification**

**NB: See Appendix 5 for the official guidelines on how to write this thesis.**

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# **Chapter one: Introduction**

## Summary

Chapter 1 describes….

**Introduction – a high level description of the research question and the problem domain that can be understood by somebody new to the subject area.**

* + **Objectives –** A single sentence that describes the purpose of this section.
  + **Research Question** – State the technical problem that you have focused on in your project in the form of a question which you address.
  + **Motivation** – Discuss the reasons for solving this problem. Detail the problem domain and who would be interested in the solution. Describe the likely impact of your work. Address both why it is an interesting technical problem, and also the value of solving it in more general terms.
  + **Aims and Objectives** – State the aims and objectives of your project. The **aims** of your project are the overall goal, and the **objectives** are the stepping stones in reaching that goal. Identifying the objectives helps the reader to understand your overall project approach.
  + **Report Structure** - Outline the structure of the report summarizing each chapter in one sentence.

## 1.1 Overview

Formal specification and software verification of software have become increasingly pertinent in the past decade, as a way of supplementing the already popular software testing techniques, to both improve software quality and provide a more concrete proof of reliability. This lead to the Programming by Contract approach that was popularised by Bertrand Meyer (*Meyer, B. 1992*) , however was presented in earlier works (Insert Works?), with the overall goal being to reduce defensive programming and increase reliability by introducing mathematical proofs into a methods specification, therefore enforcing the clients and suppliers compliance (InsertQuote?).

However, the use of these proof techniques has not been wholly adopted by industry due to business factors such as the time required for specifying the source code and costs related to such a process, to the more technical factors such as the difficulty in specifying and verifying code with the current tools and languages available, with an expert in the domain often required to get valid implementations.

## 1.2 Motivation

‘VerifyThis’ (Pm.inf.ethz.ch. (2018) is a program verification competition that requires contestants to specify and verify a certain number of tasks within a certain time limit, usually 45 minutes per question. The winners of these competitions in the past five years, 2018 included, were teams that used the verification tools Isabelle, Why3, KIV, Verifast with KeY and Dafny also proving popular. These tools, with the exception perhaps of Dafny, are non-intuitive by nature and require vast amounts of expertise and skill to master with no regular cross-over functionality between them or interface to connect them (Source).

The developers of these tools do not communicate regularly (Source) with each other and focus primarily of developing their own tool’s functionality. This lack of co-ordination has led to many different tools that, even though proven to work, are not adopted by many users outside of their field. Novice users, just coming into the formal verification domain, especially have a steep learning curve with separate libraries and syntax variables to conquer while trying to embrace the core concepts of Programming by Contract. This lack of co-operation and co-ordination has increased the delay of verification being adopted outside of academia with industry primarily focused on developing software products in a timely, cost effective matter. Ensuring reliability is paramount to all software development projects, however the time and expertise required for integrating one of the verification tools above seems to be too much for industry to handle and relies primarily on the proven but not fully sound software testing techniques (Source).

OpenJML aims to bridge this gap (Source) by allowing its freely available tool to be integrated into the Eclipse IDE directly and using only the popular JML specification language with sequential Java programs. A command-line tool is also available and the overall goal of the tool is simplicity for novice and expert users alike. This project aims to evaluate how easy in fact it is to use this tool in comparison to its competitors, KeY also has an Eclipse plugin, and if the stripping down to just the basics of JML with Java would be viable for real-life industrial systems.

## 1.3 Objectives

The main goal of this project is to determine how effective OpenJML can be at specifying software programs with its use of JML and determine if the verification tool can provide adequate and accurately valid results for said specifications. We set out to solve programs from the VerifyThis 2012 competition, specifically the PrefixSum and Longest Repeating Substring questions, as they have been specified and verified by other tools with a clear benchmark in place for comparison.

From the OpenJML Deductive Verification process we hoped to determine its difficulty, adaptability and usability in working with these programs and therefore determine its validity in comparison to other similar tools such as KeY and Why3.

We also would provide feedback and data to the developer, David R. Cok, of the OpenJML tool as we progress through our implementations; reporting issues, bugs and specification difficulties for both assistance and possible recommended updates that may be required. Our overall goal was to determine if the OpenJML tool is complete enough to replace all other verification tools and streamline the formal verification academic area to focus solely on this tool moving forward reducing complexity for users and with the hope of widespread adoption in both academia and industry alike.

## 1.4 Approach

Summarise how you addressed solving the problem.

Provide an overview of how you analysed the problem, how you designed a solution, and how you evaluated your solution. (e.g. use of models, simulation, prototypes, real-world experiments, cases studies, etc.). What important variables did you control, ignore, or measure in your evaluation.

PrefixSum

Longest Repeating Substring

We started the process by selecting two programs from the VerifyThis 2012 competition, PrefixSum and Longest Repeating Substring.

## 1.5 Metrics

Describe how you are going to evaluate your work.

Comparison to KeY and Why3 tools on similar programs.

* Lines of code
* Specification differences
  + Difficulty
  + Adpatability
  + Usability
  + Validity
* Libraries
* Proof Obligations
* Proof Discharges
* Symbolic Execution vs VCG
* Standalone tools vs Plugins
* Valid proofs

## 1.6 Project

List, and briefly describe your significant achievements in the project (probably 3-5 of these in a typical project). If you have come up with any contributions

# **Chapter two: Related Work**

## Summary

The purpose of this chapter is to show your depth and breadth of reading and understanding of the problem domain

**Related Work – Details what others have done that is relevant to your work.**

* + **Objectives –** A single sentence that describes the purpose of this section.
  + Describe the context of the research question in detail, defining terminology, and with references.
  + Explain how the problem, or related problems, has been solved previously. Critically analyze existing solutions. Discuss how your approach compares to these solutions.
  + Explain other techniques that you have used to: help understand and analyze the research question; motivate your own work; evaluate your solution.

## 2.1 Topic material

(Research material, if used, from published journals and conference proceedings; less academic publications, if required by the project, from other sources) – for example, what other work researchers have done already in this area, what results they have produced, what work has been done in related areas, what software already exists to solve this or similar problems, etc.

Literary Review

* History
  + Deductive Verification (Transitional Systems) vs Testing
  + Hoare Logic
    - Rules
  + First-Order Logic
  + DbC
    - Precondition
    - Postcondition
    - Assertions
    - Invariants
    - Client
    - Supplier
  + RAC
    - Purpose
  + ESC/Java2
    - Purpose
* Theorom Provers (Paragraph)
  + Isabelle
  + PVS (Prototype Verification System)
* Deductive Verifiers
  + JML
    - Language syntax
    - Capabilities
    - Drawbacks
  + OpenJML
    - Purpose
    - VCG
    - Eclipse
    - Command Line
  + Why3
    - WhyML
    - Krakatoa
    - Command Line
  + KeY
    - Symbolic Execution
    - Java Dynamic Logic
    - Taclets

The KeY tool was created by [Reiner Hähnle](https://www.se.informatik.tu-darmstadt.de/de/se/group-members/reiner-haehnle/), Wolfram Menzel, and [Peter Schmitt](https://lfm.iti.kit.edu/pschmitt.php) at University of Karlsruhe in 1998 *(Schmitt, P., Tonin, I., Wonnemann, C., Jenn, E., Leriche, S. & Hunt, J. (2006))*. It was developed as a source-code based verification system to be used for Java programs along with their specifications written in the Java Modelling Language (JML).



Figure 1: The KeY Verification Workflow

*(Ahrendt, W., Beckert, B., Bubel, R., Hähnle, R. Schmitt, P., & Ulbrich, M. (2016))*.

JML KeY version with Libraries

The ideal programs KeY was designed for were sequential, therefore not concurrent, programs with the objective being to *‘integrate design, implementation, formal specification and formal verification of object-oriented software as seamlessly as* possible*’ (Ahrendt, W., Beckert, B., Hähnle, R., Rümmer, P. & Schmitt (2007)).*

The KeY tool has a dedicated interactive theorem prover that lets the user find a proof, provide values for quantifier instantiations and step through each proof in stages. It provides its own standalone IDE for applying direct proof obligations as well as a plugin for the Eclipse IDE, however the Eclipse plugin cannot apply direct proof obligations to code. The KeY IDE also has an automated feature which will automatically select the optimal SMT solver and proof strategy for each section of code, this technique was used in KeY to avoid a common human interpretation issue with counter examples that are generated, usually, in Normal-Form (*Burns, D., Mostowski, W. & Ulbrich, M. (2015))*. If a SMT solver fails to provide a complete proof for a certain section of the code; the user can use the KeY IDE to select a different SMT Solver for that specific section, e.g Alt-Ergo is better for arithmetical proofs than z3. The proof strategies employed by the KeY automated verification tool ‘*provides compound interaction steps combine the application of several basic deductionsteps to achieve a specific purpose*’ and are defined as:

* + *Propositional expansion* (without splits) apply only non-splitting propositional rules
  + *Propositional expansion* (with splits) apply only non-splitting propositional rules
  + *Finish symbolic execution* apply only rules for modal operators
  + *Close provable goals* automatically close all open goals for which possible

(*Burns, D., Mostowski, W. & Ulbrich, M. (2015))*

Using the Design by Contract paradigm, KeY was built to support modular verification and in 2013, KeY 2.0 was released which allowed recursive method implementations to be modularly verified (*Burns, D., Mostowski, W. & Ulbrich, M. (2015))*.

The construction of proofs in KeY is done differently to most other deductive verifiers. Instead of using the popular Verification Condition Generation (VCG) technique, which uses weakest precondition calculus to transform a program into one single proof obligation formula to then be discharged using a general purpose theorem , it uses the symbolic execution technique. This technique axiomatizes the program logic into a sequent calculus, written in a taclet language, to determine the final state constraints for each possible branch in the program, which are then evaluated by the provers (*Burns, D., Mostowski, W. & Ulbrich, M. (2015))*. *‘This process was used as it provided more feedback to the user since the formulae are more human-readable and allows for the debugging of said program’* (*Burns, D., Mostowski, W. & Ulbrich, M. (2015))*. ‘*Taclets are a concise description of rules that specify the logical content, context and pragmatics of its application*’ *(Ahrendt, W., Beckert, B., Hähnle, R., Rümmer, P. & Schmitt (2007)).* To perform this technique the statements of the program are expanded into simpler equivalent expressions, a process called unfolding that provides syntactic updates, and continues this process until all statements can no longer be simplified. Local variables are added to the expressions to hold intermediate computation results and then case distinctions are developed based on possible scenarios that could occur with the statement.

* o.next.prev=o;io.next.prev := o
* <ListEl v; v=o.next; v.prev=o;> o.next.prev := o
* o != null 🡺 {v := o.next} <v.prev=o;> o.next.prev = o
* o == null 🡺 {throw new NullPointerException();> o.next.prev = o

*(Ahrendt, W., Beckert, B., Bubel, R., Hähnle, R. Schmitt, P., & Ulbrich, M. (2016))*.

The two processes combined (syntactic updates and case distinctions) are the essence of symbolic execution and work for normal Java statements but require further details, loop\_invariants, when dealing with loops as the unwinding process would be unbounded resulting in continuous interations. ‘Method invocations should be symbolically executed using a methods contract to ensure it is only symbolically executed once’ *(Ahrendt, W., Beckert, B., Bubel, R., Hähnle, R. Schmitt, P., & Ulbrich, M. (2016))*.

Java Dynamic Logic is the basis of the KeY logic system. It is a typed first-order predicate logic with subtyping extended; the type system was designed to match the Java type system to reduce the learning curve required when using the tool. It uses parameterised modal operators (p) and [p], where p can be any sequence of legal Java statements which refer to the final state of program p, with (p)ɸ expressing that the program p terminates in a state which ɸ holds and [p]ɸ expressing that p does not demand termination but it if did then ɸ holds. Another type of modal operator, ‘updates’, describes program transitions that are stated as ‘*simple function updates corresponding to assignments in an imperative programming language, which in turn can be composed sequentially and used to form parallel or quantified updates’ (Ahrendt, W., Beckert, B., Hähnle, R., Rümmer, P. & Schmitt (2007)).* Verification calculus transforms programs into updates with the KeY tool simplifying them to apply to formulas.

* SMT Solvers
  + Alt-Ergo
  + Z3
  + Coq

## 2.2 Technical material

(From any source: including books, websites) – for example, how to write a web server, how to use specific Java features, how to use Ajax, how to use UML to validate your design, etc.

NB: Note that material relating to the motivation or non-technical background should **NOT** go here, but rather in the introduction

Examples

* Hoare Logic
* DbC
* JML
* OpenJML
* Why3
* KeY
* Z3

### KeY Deductive Verification Tool

# **Chapter three: The Problem**

## Summary

The purpose of this chapter is to clearly explain the technical problem and/or identify the user requirements.

## 3.1 Project UML documentation

Provide any model(s) of the problem (e.g. equations, ERD’s, UML Use Cases & Scenarios, Activity Diagrams, etc.)



Figure 3‑1 UML class diagram overview for this project.

## 3.2 Problem analysis

Provide any analysis of the problem, leading to a greater understanding

There should be no decisions made in this chapter

# **Chapter four: The Solution**

## Summary

The purpose of this chapter is to clearly identify, discuss, and justify the decisions you made.

“**Solution” (often the name of your solution) – Details what you have done and how you have done it.**

* + **Objectives –** A single sentence that describes the purpose of this section.
  + Provide an analysis of the problem, motivating your approach to answering the research question.
  + Explain your approach by describing exactly what you have done.
  + Explain how you have achieved your solution. Examples: explain how a process improvement was implemented, how a mathematical technique was derived, or how an algorithm was implemented.

## Depending on your type of project, you may not need to include all of these:

## 4.1 Analytical Work

E.g. Equations, etc. that describe your solution

## 4.2 Architectural Level

E.g. Implementation Diagrams

## 4.2 High Level

## E.g. Packages, Class Diagrams, etc.

## 4.2 Low Level

## E.g. Method specifications, Algorithms, etc.

## 4.2 Implementation

Discuss anything interesting here; put full source code in an appendix or attachment

# **Chapter five: Evaluation**

## Summary

Chapter 5 describes……..

**Evaluation – Evaluates your work (both in absolute terms, and compared to other solutions)**

* + **Objectives –** A single sentence that describes the purpose of this section.
  + Explain what was evaluated or validated.
  + Experimental setup – Detail how you evaluated and validated your work.
  + Present your results clearly and objectively, without interpretation - ideally with graphs (data)
  + Explain your results - ideally with explanatory text (analysis) to both explain the meaning of these results, and provide the reasons for why these particular results were obtained
  + Critically analyze your results. Identify the contents in which your results are relevant and any threats are to the validity of your results. Show how well you have answered the research question.
  + Critically analyze your results with respect to the “Related Work” presented earlier.

## 5.1 Solution Verification

## E.g. use your equations to verify the correctness of your solution

## 5.2 Software Design Verification

How did you show that your design worked properly?

Using a model of your solution. E.g. use UML interaction diagrams to verify each scenario.

## 5.3 Software Verification

How did you demonstrate your software worked properly?

If you have not tested your software, then you cannot rely on your results. Clearly describe:

### 5.3.1 Your test approach (i.e. unit testing, sub-system testing, system testing)

### 5.3.2 Your tests (e.g. scenarios, test cases, test data, etc.)

### 5.3.3 Your test results

### 5.3.4 An interpretation of the results

## 5.4 Validation/Measurements

How did you measure how well your solution solved the problem.

### 5.4.1 Results

### 5.4.2 Explanation of Results

### 5.4.3 Analysis of Results

### 5.4.4 Comparison with previous solutions (if relevant)

**Chapter five: Conclusion**

**Summary**

Chapter 5 identifies and discuss the implications of your work.

**Draws conclusions and identifies potential future work**

* + **Objectives –** A single sentence that describes the purpose of this section.
  + Summarize your results. Provide your conclusions (limitations & recommendations) based on the results obtained. Detail the implications of your results with respect to the wider community.
  + Assess how well you have met your project goals. Identify the contributions made by this work.
  + Critically analyze your approach to solving the research question by explaining what was effective in your approach, and what you could have been improved upon.
  + Present possible future work - How could you/others build on your research to advance it further?

5.1 Contribution to the state-of-the-art

If you made a contribution to the state-of-the-art, clearly identify it here.

5.2 Results discussion

Discuss whether your results are general, potentially generalizable, or specific to a particular case. Identify threats to the validity of your results (e.g. limitations, risks introduced by your approach, etc.)

5.3 Project Approach

Discuss your project approach

5.3 Future Work

Discuss future work, based on what you have done (and not done)

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**Appendices**

Include here all extra material, e.g. your source code, project management (optional) including: the task list, Gantt Chart diagrams (or equivalent), discussion of any significant deviations from plan, and how you managed them, discussion of what you would do differently if you repeated the project.

## Appendix 1 Schematic of the hardware associated with this project.

## Appendix 2 Code developed for this project.

## Appendix 3 UML Class, Use Case and sequence diagrams for this project.

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| Appendix 4 Screen shots of the project implementation |
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## Appendix 5 Taught M.Sc. Dissertation Guidelines (valid from Oct 2015)

**Taught M.Sc. Dissertation Guidelines**

**(valid from October, 2015)**

This document provides guidelines for your M.Sc. level dissertation for modules CS640 and CS645. There is no standard layout (except for the cover page), as the details may be determined by the project topic and the approach you have taken. You should read a number of other dissertations (available on Moodle or from ePrints) to get an idea of the accepted norms. Your supervisor will be able to advise you further.

Your dissertation won't necessarily be *organised* as shown here, but it MUST *contain* the following information:

* Title
* Abstract
* Introduction
* Related Work
* “Solution” (i.e. title of your work)
* Evaluation
* Conclusions
* References
* Appendices

How you present the research question and your solution will depend to a certain extent on the nature of your project. You need to show that you are aware of other research in the area, and show the relationship of at least one other publication to your own work.

The dissertation absolute limit is 22,000 words (using size 12 Times New Roman font and single line spacing, and not including the appendices). A suggested format for your report is detailed on the next page. Supporting documentation such as your documented code should be uploaded separately as directed by your course co-ordinator. **The submission must be all your own work**. Please read the Maynooth University policy on Plagiarism and ensure that your reference material correctly. The minimum penalty for plagiarism is a failed grade in your thesis.

Recommendation: agree on a “model” report with your supervisor that you can base your approach and layout on. The following diagram shows the ‘flow’ or ‘argument’ you should use in presenting your work.



**Title Page** - Template on next page (replace the highlighted text).

**Abstract -** This is a summary of the research question, your results, and your contribution in 200 words or less.

**Category, Terms, Keywords:** reference [www.**acm**.org/sigs/**publications**/pubform.doc](http://www.acm.org/sigs/publications/pubform.doc)for details

**Suggested sections and sub-sections**

* **Introduction – a high level description of the research question and the problem domain that can be understood by somebody new to the subject area.**
  + **Objectives –** A single sentence that describes the purpose of this section.
  + **Research Question** – State the technical problem that you have focused on in your project in the form of a question which you address.
  + **Motivation** – Discuss the reasons for solving this problem. Detail the problem domain and who would be interested in the solution. Describe the likely impact of your work. Address both why it is an interesting technical problem, and also the value of solving it in more general terms.
  + **Aims and Objectives** – State the aims and objectives of your project. The **aims** of your project are the overall goal, and the **objectives** are the stepping stones in reaching that goal. Identifying the objectives helps the reader to understand your overall project approach.
  + **Report Structure** - Outline the structure of the report summarizing each chapter in one sentence.
* **Related Work – Details what others have done that is relevant to your work.**
  + **Objectives –** A single sentence that describes the purpose of this section.
  + Describe the context of the research question in detail, defining terminology, and with references.
  + Explain how the problem, or related problems, has been solved previously. Critically analyze existing solutions. Discuss how your approach compares to these solutions.
  + Explain other techniques that you have used to: help understand and analyze the research question; motivate your own work; evaluate your solution.
* “**Solution” (often the name of your solution) – Details what you have done and how you have done it.**
  + **Objectives –** A single sentence that describes the purpose of this section.
  + Provide an analysis of the problem, motivating your approach to answering the research question.
  + Explain your approach by describing exactly what you have done.
  + Explain how you have achieved your solution. Examples: explain how a process improvement was implemented, how a mathematical technique was derived, or how an algorithm was implemented.
* **Evaluation – Evaluates your work (both in absolute terms, and compared to other solutions)**
  + **Objectives –** A single sentence that describes the purpose of this section.
  + Explain what was evaluated or validated.
  + Experimental setup – Detail how you evaluated and validated your work.
  + Present your results clearly and objectively, without interpretation - ideally with graphs (data)
  + Explain your results - ideally with explanatory text (analysis) to both explain the meaning of these results, and provide the reasons for why these particular results were obtained
  + Critically analyze your results. Identify the contents in which your results are relevant and any threats are to the validity of your results. Show how well you have answered the research question.
  + Critically analyze your results with respect to the “Related Work” presented earlier.
* **Conclusions – Draws conclusions and identifies potential future work**
  + **Objectives –** A single sentence that describes the purpose of this section.
  + Summarize your results. Provide your conclusions (limitations & recommendations) based on the results obtained. Detail the implications of your results with respect to the wider community.
  + Assess how well you have met your project goals. Identify the contributions made by this work.
  + Critically analyze your approach to solving the research question by explaining what was effective in your approach, and what you could have been improved upon.
  + Present possible future work - How could you/others build on your research to advance it further?

**References –** Proper full complete citations for all referenced documents (NOT a URL). For a master’s level document one would expect up to 30 good references. Use peer-reviewed papers or books: not websites.

**Appendix** – Details of: source code, protocols, data, results, etc.

**Note** – Use a repository to store your code & build procedure.